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SCINTILLATION EFFECTS, MITIGATIONS AND RECOMMENDATIONS FOR AFSA--ETC(U)
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AFCC TECHNICAL REPORT

# SCINTILLATION EFFECTS, MITIGATIONS

# AND

# RECOMMENDATIONS FOR AFSATCOM

# AND

# OTHER SATELLITE COMMUNICATIONS SYSTEMS

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Radio Systems Branch
1842 Electronics Engineering Group (EEG)
Air Force Communications Command (AFCC)
Scott Air Force Base, Illinois

15 June 1981

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Signal propagation disturbances, such as scintillations, seriously degrade or disrupt operational performance of AFSATCOM and other satellite communication links. The ionospheric irregularities which cause these disturbances may develop in either a natural or nuclear environment. Natural scintillations correlate with location, time of day, season and solar activity, and are particularly disruptive to airborne (SIOP) communications terminals. The disruptions are expected to peak in the early 1980's, near the crest of the 11 year solar activity cycle. Nuclear detonations can produce a combination of absorption

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and intense scintillation extending over a CONUS size region for several hours at UHF, and somewhat less at SHF. The report discusses both types of scintillation, noting the analogous equations governing density functions in the two regimes, outlines mitigation strategies, reviews Air Force involvement and offers recommendation for a coordinated and integrated AF effort. The AFCC/1842 EEG mission requirements, to perform system engineering, consultative assistance to MAJCOMs, and collaboration in research and development is reviewed and recommendations are made as to method to meet these requirements.

## APPROVAL PAGE

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## SUMMARY

This report surveys a portion of the literature on scintillation, discusses its impact on Air Force and other military satellite communications systems, reviews mitigation strategies, outlines technical effort by Air Force organizations involved in scintillation, including the 1842d Electronics Engineering Group, and offers some recommendations intended to focus and coordinate the Air Force response to increasingly severe scintillation disruptions in our satellite data links.

## RECOGNITION

The author wishes to thank Dr. K.C. Yeh of the University of Illinois, Dr. Jules Aaron of Air Force Geophysics Lab (AFGL) and Mr. Alan Johnson of Air Force Avionics Lab (AFAL) for valuable assistance in this effort. Dr. Sidney L. Ossakow of the Naval Research Laboratories provided special assistance and valuable insights which were most helpful in dealing with nuclear phenomena as it affects satellite communications links. Mr. Arthur Davis of the 1842d also provided valuable suggestions for our work. Appreciation is also due to the staff of Washington University Engineering Department and Library for providing most of the reference material used in the report.

## 1.0 INTRODUCTION.

1.1 GENERAL. This report summarizes investigations of signal propagation disturbances such as satellite communications and data links caused by natural and nuclear environments. Recommendations are made for a concerted Air Force response to the problem. These disturbances are caused by differing degrees of sharply increased levels of ionization in the F-region of the upper atmosphere. Their severity is related to the magnitude and structure of electron concentration. The significance of the disturbances is related to system characteristics such as carrier frequency, signal bandwidth, receiver antenna design, modulation techniques and demodulator design.

1.2 TYPES OF DISTURBANCES. The most serious natural disturbances are amplitude and phase scintillations. Signal absorption and amplitude and phase scintillations are the most serious disturbances generated in a nuclear environment.

1.2.1 Natural ionospheric scintillations are presently causing intermittent but severe disruption of UHF and higher frequency satellite communication links, such as AFSATCOM, particularly in equatorial, auroral and polar latitudes. This disruption particularly affects airborne SIOP force terminals operating in these latitudes. The disruptions are expected to increase through the 1982-83 crest of the 11 year cycle of solar activity.

1.2.2 Satellite links to ground and airborne terminals, particularly links operating in the lower part of the UHF band, are subject to potentially serious degradation by propagation disturbances in a nuclear environment. Large yield detonations at altitudes above 100 km pose the greatest threat to link survivability. Signal absorption and scintillation are the most serious propagation disturbances in such environments.

1.2.2.1 Absorption produced communication blackouts may affect an area of several hundred kilometers in extent for some minutes after a single, large yield, high altitude detonation.

1.2.2.2 Signal scintillation is a much more widespread and long lasting propagation disturbance following a high altitude nuclear detonation. A single detonation can produce intense UHF scintillations over a CONUS sized area which may persist for several hours. As frequency increases, both the area of coverage and the period of intensity of scintillations tend to decrease.

## 2.0. PRELIMINARY CONSIDERATIONS.

2.1 DEFINITION. The propagation of electromagnetic waves passing through an inhomogenous ionosphere results in changes or variations in amplitude, phase and angle of arrival of the waves at the receiving point. These variations are known collectively as scintillations. The variations are caused by ionospheric irregularities along the transmission path resulting from significant electron depletion, when compared with the surrounding F-region. The large gradients in electron density produced by these depletions cause corresponding changes in the refractive index resulting in phase and amplitude scintillations.

2.2 ANALYSIS. Analysis of transmission propagation disturbances follow one of the following theoretical approaches:

2.2.1 The problem may be treated as one involving scattering, a process of diffusing the electromagnetic radiation by reflection from molecules, atoms, electrons or other particles.

2.2.2 A second approach utilizes diffraction theory and presupposes the concept of a ficticious equivalent thin "phase" screen to calculate detailed structure of the wavefield.

2.2.3 A formulation involving ray optics may be used.

2.3 CLASSIFICATION. Both amplitude and phase scintillations may occur and can be characterized by a depth of fading index, a fading period, and a phase delay. Appendix IV describes these parameters in detail.

## 3.0 NATURAL SCINTILLATION PHENOMENA.

3.1 LATITUDINAL CONSIDERATIONS. Scintillation related phenomena, as other ionospheric and atmospheric parameters, display geographical characteristics which appear to divide the earth into three main latitudinal zones. Scintillation correlation and morphology in these zones are discussed below.

3.1.1 Correlations with Solar, Magnetic and Other Phenomena.

3.1.1.1 An equatorial zone extends from the equator to a latitude of $\pm 20^{o}$ and is a region of intense and diurnal scintillation activity. Equatorial scintillation appears to be negatively correlated to magnetic index ($K_p$) and positively correlated to solar flux ($S_f$). It appears to be correlated to diurnal and seasonal change.

Equatorial Scintillation Index = f ($-K_p$, $S_f$, Time of Day, Season) Eq 1

3.1.1.2 A mid-latitude zone extends from latitude of $\pm 20^{o}$ to the auroral regions around $\pm 65^{o}$, and displays quiet to moderately active scintillation. The auroral region index is positively correlated with both magnetic index ($K_p$) and solar flux ($S_f$) with time of day and seasonal correlation in evidence.

Auroral Scintillation Index = f ($K_p$, $S_f$, Time of Day, Season) Eq 2

3.1.1.3 The polar region, normally considered as latitudes above $\pm 65^{o}$, is the area of moderate to active scintillations. Initial observations have been limited but indicate that scintillation is strongly correlated with solar flux ($S_f$) and season with little correlation with magnetic index or time of day.

Polar Scintillation Index = f ($S_f$, Season) Eq 3

3.1.2 Discussions and Morphological Studies. (Ref Figure 1)

3.1.2.1 Equatorial Scintillations - The probable sites, oı origins of ionospheric irregularities, or scintillations, have been variously described as bubbles, plumes, patches, irregularities, disturbances and plasma (electron) density depletions.

3.1.2.1.1 Equatorial scintillation is predominantly a night time phenomena, usually occurring one to two hours after local sunset. It is hypothesized that the occurrence results from sharp electron density irregularities which develop at altitudes of 200-300 km expanding and rising rapidly to altitudes of 700 to 1000 km. These irregularities turn into plume and bubble configurations. The initiation or triggering process is uncertain[(3), (8), (16)] (Ref: Figure 2 & 3).

3.1.2.1.2 These bubbles, or electron depletions, have been verified by examining their effects on radio propagation utilizing Faraday rotation techniques[(25), (26), (27)]. Electron depletion levels exceeding 20% have been noted by Klobucher. Additional in situ

measurements utilizing rockets and satellites have revealed a spiky wedgelike electron density structure inside the equatorial bubbles [26], [27]. Computer simulations of radio propagation through such bubbles have shown that these sharp gradients of electron density result in large amplitude scintillations, especially at gigahertz frequencies [25].

3.1.2.1.3 Once formed, these bubble irregularities drift eastward at 100-200 meters/second. Individual bubbles have been tracked for over 3 hours using an all sky photometer operating at 6500 Å to measure air glow. Irregular patches may have an east-west extent of 2000 km and north-south dimensions of 50 to 200 km. They may occur as a series of disturbed ionospheric patches extending along the equator with a thin, irregular structure (causing only minor scintillations) connecting the larger disturbed patches. This connecting fabric appears to diminish with distance from the equator leaving the field aligned irregularities separated by undisturbed ionosphere.

3.1.2.1.4 Occurrences of equatorial ionospheric disturbances appear to increase during sun spot maxima. There appears to be a negative correlation between equatorial activity and magnetic indices. A seasonal pattern of activity is observed with variation depending upon the location along the magnetic equator. Peaks are experienced at equinox periods and remaining strong through local summer. A minimum occurs during local winter.

3.1.2.1.5 Originally, it was believed that scintillation disturbances, characterized primarily by slow fading rates, affected electromagnetic transmission on VHF and part of UHF only. Recent studies have identified scintillation fades exceeding 25dB at 1.5 GHz, and 3dB at 8 GHz. These fades are characterized by fast fading rates, apparently closely associated with spread-F region irregularities as seen on bottom side ionograms.

3.1.2.2 Scintillation in the lower mid-latitudes between $20^{o}$ and $50^{o}$ North and South is a relatively rare phenomenon. As one approaches the auroral oval above $50^{o}$ North or South a seasonal pattern of light to medium scintillation emerges which varies widely with magnetic index and diurnal variation.

3.1.2.2.1 This seasonal dependence of scintillations causes a two to one variation from summer to winter in the northern hemisphere under quiet magnetic conditions. Large gradients also occur in the latitudinal gradients of scintillation, from 2 dB/degree in summer to 1 dB/degree in winter, for latitudes above $60^{o}$ with relation to the magnetic poles. This seasonal dependence of scintillations is related to changes in the tilt angle of the earth's magnetic dipole with relation to the sun, and consequent modulation of particle precipitation of the auroral oval [2, 9, 24].

3.1.2.2.2 Aarons evaluated data from the geostationary ATS-3 satellite at 137 MHz. These data were taken at three sites along the $70^{\circ}$ meridian to formulate average scintillation valves at sub-auroral and aurcral latitudes. The data consisted of 15 minute averaged indices, taken over 3 to 7 years of observations from Sagamore Hill Mass., Goose Bay, Labrador and Narssarssuaq, Greenland. Aarons found that for a site in the auroral oval (Nassarssuaq, Greenland) scintillation occurred at levels of at least 9 dB for 61.8% of the time with $K_p$ (magnetic index) in the range of 4 to 9. This research, though limited by single frequency of observation and excursion of scintillations, determined a "Percentage of occurrence of scintillation" (peak to peak) for the area. A summary is given in Appendix III.

3.1.2.3 Studies of scintillation disturbances in polar latitudes have been limited, and much work remains to develop a complete understanding of the process as it affects radio communications.

3.1.2.3.1 The present state of knowledge of ionospheric scintillation in the polar cap region is somewhat comparable with the state of knowledge for the equatorial ionosphere a decade ago[13]. Models of the equatorial ionosphere have been proposed and partially verified, but similar work in the polar region has just begun, limited by few observation sites and the large number of geophysical processes occurring in the auroral and polar regions.

3.1.2.3.2 The polar region is characterized by small regions (1 to 10 km) of magnetic field aligned irregularities which cause ionospheric scintillation fading on ground or aircraft to satellite communication links. Fading appears to be confined to VHF and UHF regions with little effect noted at SHF. Aarons developed a model which indicates the frequency dependence of the fade depth of $f^{-1.9}$ in the polar region. The model further predicts a low probability of fading in the winter months and high probability in the summer months in both polar regions. A diurnal variation, due to movement of the auroral oval, is noted, and one concludes that fading may occur more often in the polar region than in the equatorial region but will be of smaller amplitutde.

3.1.2.3.3 Rino[19],[20] analyzing DNA-002 satellite data found amplitude and phase scintillation occurring throughout the year. An unexpected finding was a significant phase scintillation compounding amplitude scintillation conditions in the auroral oval. He concluded that polar phase scintillation appeared stronger than phase scintillation

associated with similar amplitude scintillation in the equatorial region. The findings suggest a geometric effect, in that the scintillation appear strongest along a constant "L" shell of invariant latitude[9]. This suggests that the irregularities are aligned along the magnetic field lines, which are nearly vertical near the magnetic poles, and that a greater thickness of irregularities result from looking along the field lines.

3.1.2.3.4 Investigation into scintillation effects at polar latitudes is continuing and will improve our understanding of the phenomena as new data is evaluated.

3.2. LONGITUDINAL CONSIDERATIONS IN SCINTILLATIONS. Pole to pole profiles of ionospheric composition have given detailed views of the significance of the solar geomagnetic process and have helped identify dominant longitudinal variations superimposed over latitudinal distribution of each ion species[23]. The importance and implications of this variation have not been thoroughly analyzed but appear significant. An example may be helpful. Severe scintillations which were detected near Ascension Island in the South Atlantic did not appear with the same intensity at Guam Island in the mid Pacific Ocean. A complete explanation must await further investigation and study.

## 4.0 NUCLEAR INDUCED SCINTILLATIONS.

### 4.1 PRELIMINARY CONSIDERATIONS.

4.1.1 Nuclear detonations produce a number of signal propagation disturbances which present serious problems for link survivability. Absorption and scintillation are generally the most serious disturbances over a large region for long periods of time. (Appendix I details this and other Signal Propagation Disturbances.)

4.1.2 Detonations at all altitudes present problems. Dust clouds from surface bursts produce signal alterations and scintillation that <u>increase</u> in severity with increasing frequency becoming significant at X-Band and higher frequencies. High altitude detonations produce increased ionization and striations, that produce signal absorption and scintillation which <u>decrease</u> in severity with increasing frequency, but remain significant even at EHF.

4.1.3 At UHF, a single detonation can produce intense scintillation over a CONUS sized region and persist for several hours. At SHF, the region will extend from a few hundred km to about 1000 km. At EHF, scintillation may occur over an area covering a few hundred square kilometers and persist for an hour. These effects are depicted in Figures 6 and 7.

4.1.4 The existence of signal propagation disturbances in a nuclear environment has been identified for a quarter of a century. High altitude tests such as "Teak" and "Orange" in 1958 and nuclear high altitude events in the 1962 "Fish Bowl" series generated a mass of data that has been analyzed by many workers over the past 20 years. Much of the data obtained and analyzed is maintained at the DOD Nuclear Information and Analysis Center at Santa Barbara, California.

4.1.5 The research efforts have advanced our understanding of nuclear weapon effects and reduced the uncertainties in quantitative predictions of propagation disturbances. Field measurements in the natural ionosphere involving barium "cloud" experiments, have provided much data on plasma striations and signal scintillation phenomena. These data relate directly to propagation disturbance prediction in the late-time, high altitude nuclear environment. Physical models of propagation disturbances using mean levels of ionization have been available for some time although detailed methods of calculating disturbances resulting from striated ionization structures have only recently been refined.

4.1.6 Discussion of the phenomenology of nuclear weapons effects, including problems and levels of understanding, are contained in references 30, 33 & 34. It is sufficient to note the existence of unresolved issues in areas as striation evolution, High Altitude Nuclear Explosion plume phenomena, Equatorial Spread-F phenomena and others as they impact on propagation through structured ionospheric plasmas.

4.2 PROPAGATION IN A NUCLEAR ENVIRONMENT.

4.2.1 Principal propagation disturbances following a nuclear detonation are divided into early time and late time phenomena, (late time environments extend beyond 20 minutes after detonation).

4.2.1.1 At early times, severe signal attenuation due to absorption and increased noise levels are the predominate disturbances on satellite down links. Early time attenuation by absorption is extremely severe at UHF and very severe at SHF but short lived. Duration is dependent on the specific nuclear scenario and link geometry.

4.2.1.2 At late times after detonation, signal scintillations are the principal propagation disturbance. Scattering may be a problem in some late time scenarios.

4.2.2 Scintillation, both phase and amplitude, will be extremely intense and cover a very large area for a number of hours after the nuclear event. Scintillation is generally less sensitive to scenario, and its effects must be considered in the design of satellite links regardless of operating frequency. Typical amplitude and phase scintillations are depicted in Figure 8.

4.2.3 A significant signal parameter affecting system performance in intense scintillation is the signal fading rate. Tau ($t_o$), the signal decorrelation time, is the reciprocal of signal fading rate; thus a large tau correspond to slow fading and a small tau correspond to fast fading. Tau will range from several second to the millisecond range, in intense saturated (Rayleigh) scintillation and survivable satellite systems must operate over this entire range.

4.2.4 Bogusch[28] has developed a reasonable worst case time signal description for DSP downlinks using the following:

4.2.4.1 SCINTILLATION CHARACTERISTICS.

Rayleigh Signal Statistics
$f^{-3}$ Signal Power Spectrum
Range of Decorrelation Times ($t_o$ from 0.01 to 3 seconds)

LATE TIME ATTENUATION.

UHF 3-6dB (est.) (3m. antenna)
S-Band - 2dB (3m. antenna)
X-Band - 0.3dB (3m. antenna)

DOPPLER SHIFT (Hz)

UHF = $10^4$ Hz
S-Band = $10^3$ Hz
X-Band = $10^2$ Hz

4.3 SCINTILLATIONS AND JAMMING IN NUCLEAR ENVIRONMENTS.

4.3.1 In nuclear environments, survivable satellites must contend with propagation and jamming threats. Thus, anti-jam (AJ) and anti-scintillation (AS) as techniques must be compatible and coexist. Scintillation techniques in the system architecture category are generally compatible with anti-jam techniques.

4.3.2 Two modulation strategies, frequency hopping and pseudonoise spread-spectrum, are generally used to provide anti-jam protection. Frequency hopping is generally compatible with other scintillation mitigations and is often used in conjunction with error correction coding. (See Mitigation Strategies - Appendix II.) Pseudonoise (PN) spread spectrum modulation is generally unacceptable because of problems generated when the scintillation correlation bandwidth approaches or becomes less than the modulation bandwidth.

4.3.3 Error correction coding and interleaving are generally desirable for both AJ and AS protection.

4.3.4 Other scintillation mitigations may impact on anti-jam capability and should be examined for all relevant system consequences.

## 5.0 MITIGATION TECHNIQUES AND STRATEGIES.

5.1 MISSION REQUIREMENTS. A wide range of mission requirements exist for current and future satellite systems. These are exemplified by the "present" generation satellite systems such as Air Force Satellite Communications (AFSATCOM) system, the Strategic Satellite System (SSS), the existing Fleet Satellite Communications (FLTSATCOM) system, the Global Positioning System (GPS) and the Defense Satellite Communications System (DSCS-II-III). These systems span frequency bands from UHF through EHF and utilize data rates as low as 50 to 75 bps to very high 1 to 10 Mbps.

5.1.2 Systems having an existing or future requirement to operate in a natural or nuclear scintillated environment support two fundamentally different classes of mission.

5.1.2.1 Class I includes all missions requiring continuous, uninterrupted, non-repeatable, high volume information flow during a short period of time, thus, a high data rate transmission.

5.1.2.2 Class II includes mission transmission of short, repeatable messages over a period of several minutes, thus, low data rate transmission. Dissemination of an Emergency Action Message (EAM) to strategic forces or use of the GPS navigation data are examples of this type.

5.1.3 These different classes of mission require different combinations of mitigation techniques to maintain acceptable, although degraded, performance over the wide range of conditions which may be encountered.

5.1.4 A summary of satellite link effects and mitigation methods is shown in Appendix II. This table was developed by Bogusch[26,27] et.al., for a nuclear environment but has wide application in examining mitigations of natural scintillations.

5.1.5 A wide variety of mitigation techniques has been identified. Generally, they address either modem design or system architecture. The application of mitigation techniques depends on system mission and requirements.

5.1.6 Anti-jam techniques should be considered for compatibility with proposed scintillation mitigations (anti-scintillations). See Appendix II. Considerable difficulty may be encountered in implementing certain of these mitigation strategies.

## 5.2 POTENTIAL LINK MODIFICATIONS.

5.2.1 We may choose to limit system operation protocols to regions of low scintillation probability or conversely, develop a scintillation forecast mechanism to reduce link outages by indicating scintillation free areas (AWAL & GBS have proposed versions of the scintillation forecast).

5.2.2 Increasing system radiated power is not effective against absorption in nuclear environment but may provide needed extra path margin required to operate in the naturally scintillated environment.

5.2.3 Redundant links provide a way of increasing the likelihood of having a usable path and is a worthwhile consideration for overcoming natural scintillations; however, this

approach is less effective in nuclear environment due to the very large area affected by severe scintillations. Appropriately spaced antennas can offer significant gains if antenna spacing is maintained such that the correlation coefficient of the signal is less than 0.6.

5.2.4 Time diversity schemes such as error correction coding, interleaving and message repetition can provide significant mitigation of scintillation amplitude fading effects. Message coding and interleaving schemes typically provide good reception over the intermediate range of scintillation rates. Performance, however, deteriorates at a very fast scintillation rate due to loss of signal coherence across the modulation bandwidth. Performance also degrades at slow scintillation rate due to decoder degradation caused by loss of error randomization with finite length interleavers. This degradation is unrelated to modulation type except as it affects code selection.

5.2.5 The existence of periods of signal enhancement along with periods of signal attenuation suggest the use of a time diversity system which provides for an appropriate number of message repeats to take advantage of the fading enhancement process. Preliminary analysis indicates an equivalent improvement equal to 2 dB gain in receive signal level using five extended retransmissions (repeated transmissions).

5.2.6 Improvements in transmitting or receiving antennas, terminal-satellite geometry, or changes in orbital heights offer potential to reduce scintillation.

5.2.7 Scintillation is seen as varying in amplitude, somewhat inversely proportional to frequency. If frequency is raised, scintillation should be reduced.

5.3 SYSTEM ARCHITECTURE.

5.3.1 Satellite diversity, with two or more satellites sending a common message or a proliferation of satellites with suitable interconnects, will significantly improve transmission reliability in a disturbed environment. Classified studies have been performed in this area.

5.3.2 Low orbital altitude has been shown to be useful as a mechanism to shorten transmission path lengths thus operating below the highly ionized spread-F region of extreme absorption and scintillation which follows a high altitude nuclear detonation.

## 6.0 AIR FORCE ORGANIZATIONAL INVOLVEMENT.

A number of Air Force activities are involved in various phases of the study of ionospheric disturbances and scintillations of both nuclear and natural origins. A partial listing of activities and areas of involvement is given below.

| Organization | Area of Involvement |
|---|---|
| Air Force Geophysics Laboratory<br>Hanscom AFB, MA | Research into morphology of scintillation - modeling and analysis upper atmosphere research - propagation studies. |
| Air Force Space Division<br>Los Angeles, CA | System Manager - AFSATCOM until Oct 80 - Tasked ESD to undertake scintillation studies. |
| Air Force Systems Command<br>Electronic Systems Division<br>Hanscom AFB, MA | System development managers of the Terminal segment - Tasked MITRE to undertake scintillation support study in fall 1980 at Cambridge Bay & Eielson AFB to characterize scintillation. |
| Strategic Air Command<br>Communications Division D<br>Offutt AFB, NE | Link access managers-users-Must operate in scintillation environment have requested assistance from AFCC/1842 EEG for technical support to help in scintillation problem. |
| AFCC/1842d EEG<br>Scott AFB, IL | Technical studies and review of scintillations - has mission to provide systems engineering support to MAJCOM as required, on scintillation type propagation disturbances. |

| | |
|---|---|
| Air Weather Service<br>(NWS - also GWS)<br>Offutt AFB, NE & Scott AFB, IL | Provides atmospheric data to SAC on past event (disruption) analysis Developing model to assist in forecast & analysis. |
| Air Force Avionics Laboratory<br>Wright Patterson AFB, OH | Investigation of satellite to aircraft link disturbances - studies to develop mitigation techniques - dual modems investigations. Joint studies with AFGL on polar and equatorial scintillation. |
| Air Force Weapons Laboratory<br>Kirtland AFB, NM | Nuclear phenomenology studies ionospheric disturbances - including absorption and scintillation - modeling and analysis. |

## 7.0 CONCLUSIONS.

7.1 OUTLOOK. Natural ionospheric scintillation fading is causing severe but intermittent disruptions in AFSATCOM and other satellite communication links with airborne (SIOP) terminals being particularly vulnerable. Scintillations are most pronounced in equatorial, auroral and polar latitudes. The disruptions are expected to reach a maximum during the cresting of the current 11 year solar activity cycle in the early 1980's.

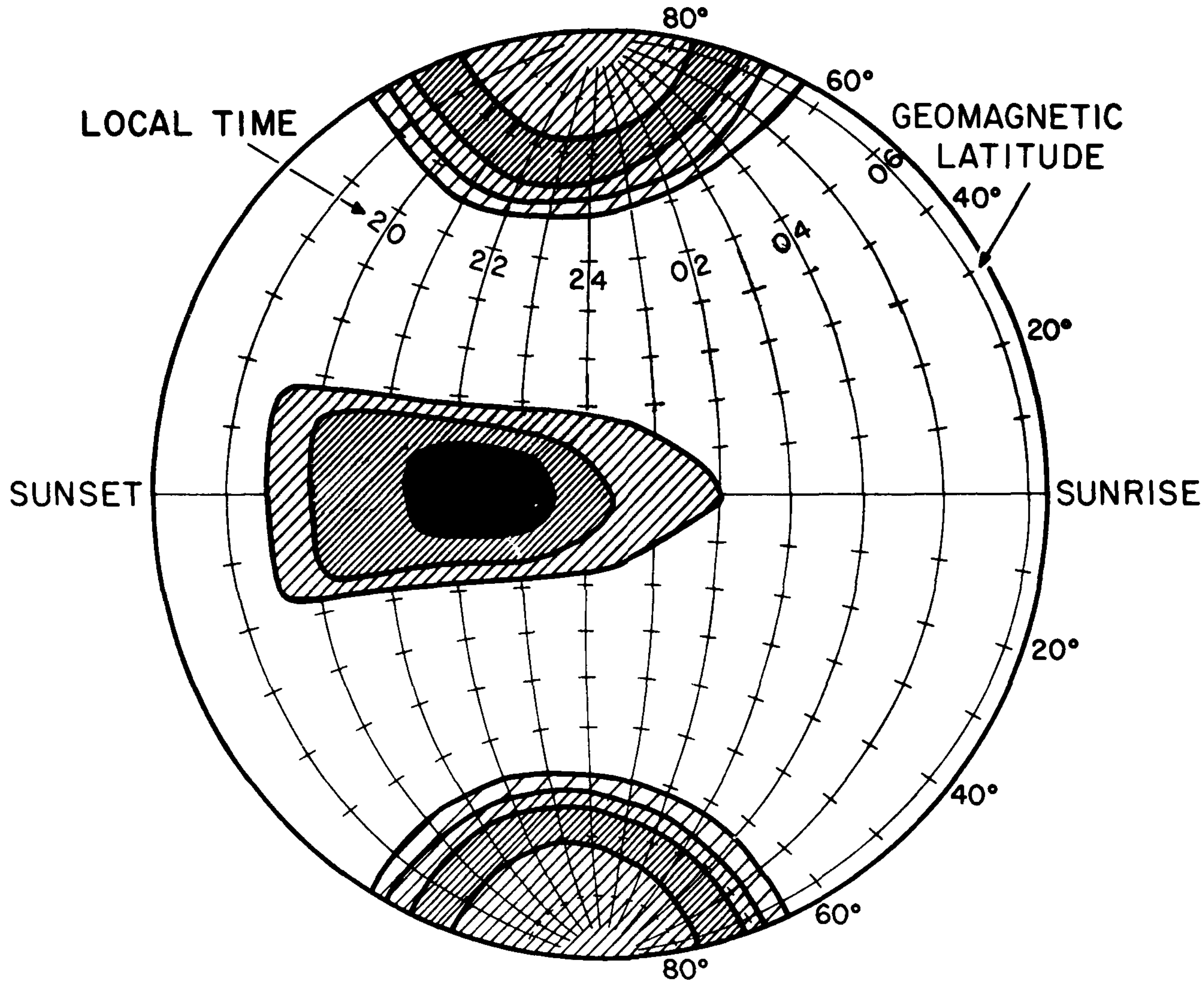
7.1.1 Scintillations produced by a single high altitude nuclear detonation can disrupt communications over a CONUS size area for several hours at UHF.

7.2 RECOMMENDATIONS. A coordinated, and well focused, Air Force effort is needed to properly address the scintillation disruption potential and implement system changes to mitigate the effects of scintillation.

7.2.1 Mitigation philosophies and strategies as suggested here, and elsewhere, should be reviewed by a team of cognizant AF systems engineering personnel to determine their applicability, priority, and operational effectiveness. Implementation should then proceed with dispatch.

7.2.2 Improved ionospheric modeling is essential to a more complete understanding and prediction of scintillation disruptions. Several data gathering and relaying systems have been proposed to support model generation and prediction by AWAL and GWS. The use of nuclear data and modeling strategies of DNA should be reviewed and incorporated where applicable.

7.2.3 The communications aspects of scintillations, which are required to assure or maintain minimum operational communications capability in a disturbed environment, need added emphasis by Air Force systems and applications specialists.




DEPTH OF SCINTILLATION FADING (PROPORTIONAL TO DENSITY OF CROSSHATCHING)

Figure 1. Geographic Distribution of Ionospheric Scintillation Fading (From Aarons)

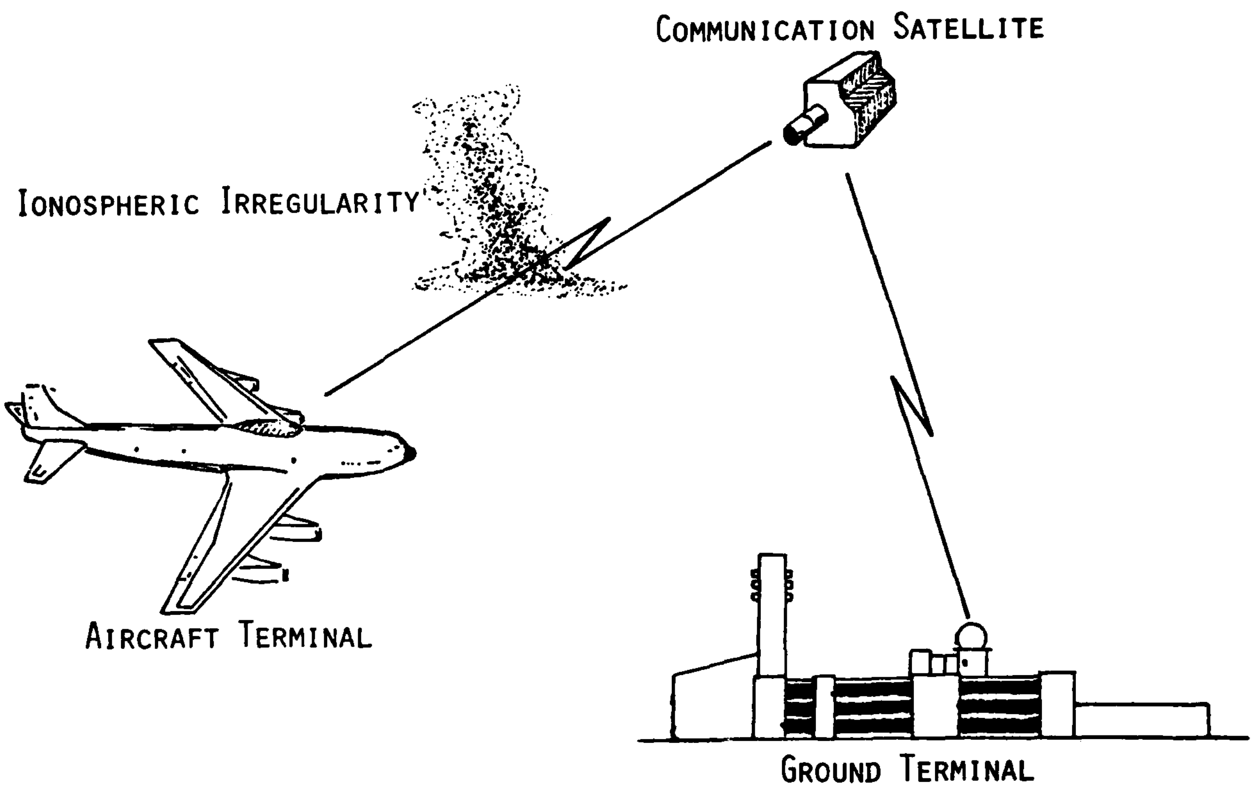



Figure 2. Typical satellite communications link showing ionospheric irregularities on satellite to aircraft link. Irregularities occur on terminal to satellite link but are less disruptive because of higher path margins.

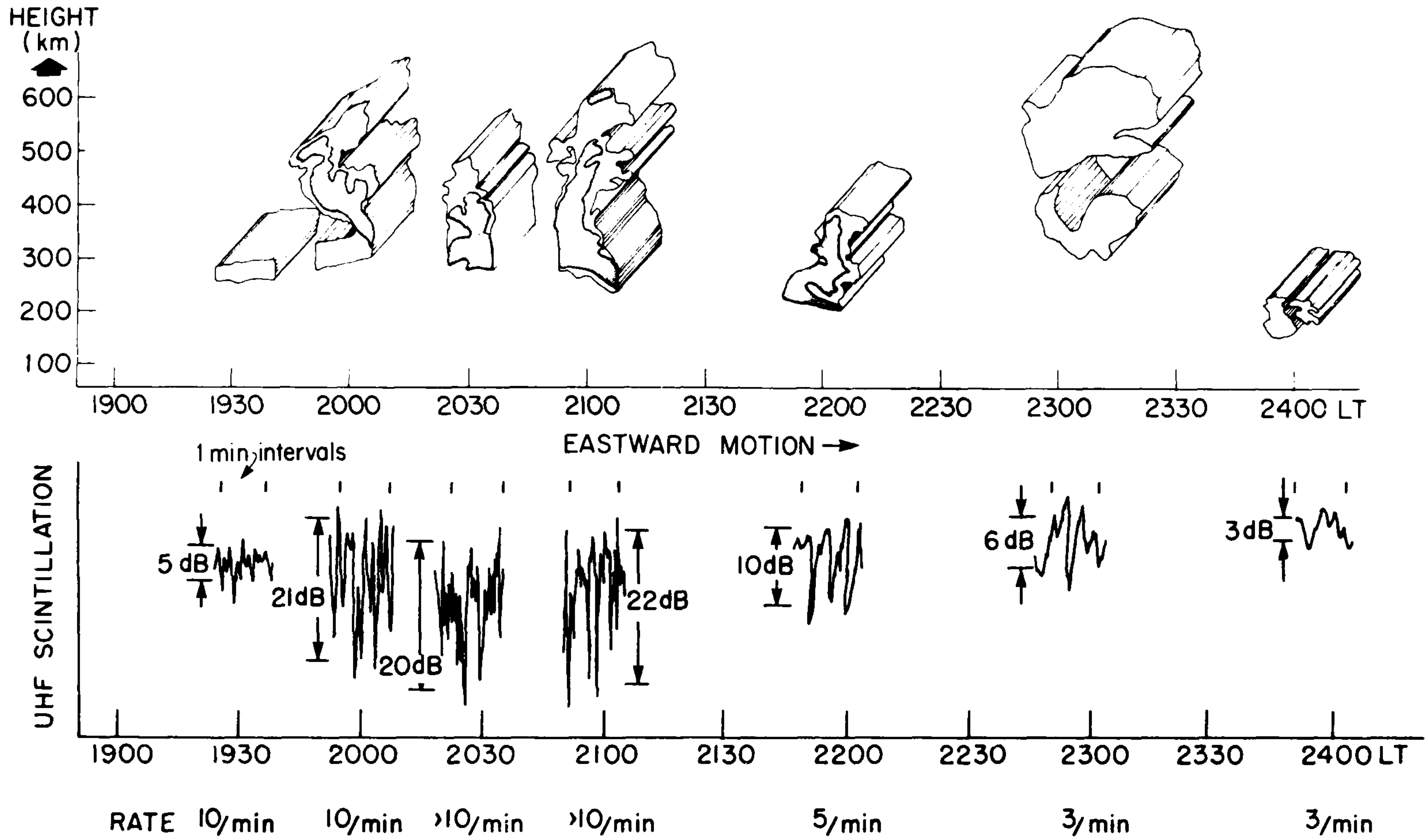



Figure 3. Typical patch development with associated scintillation amplitude and rates. ( From Aarons [1,2] )

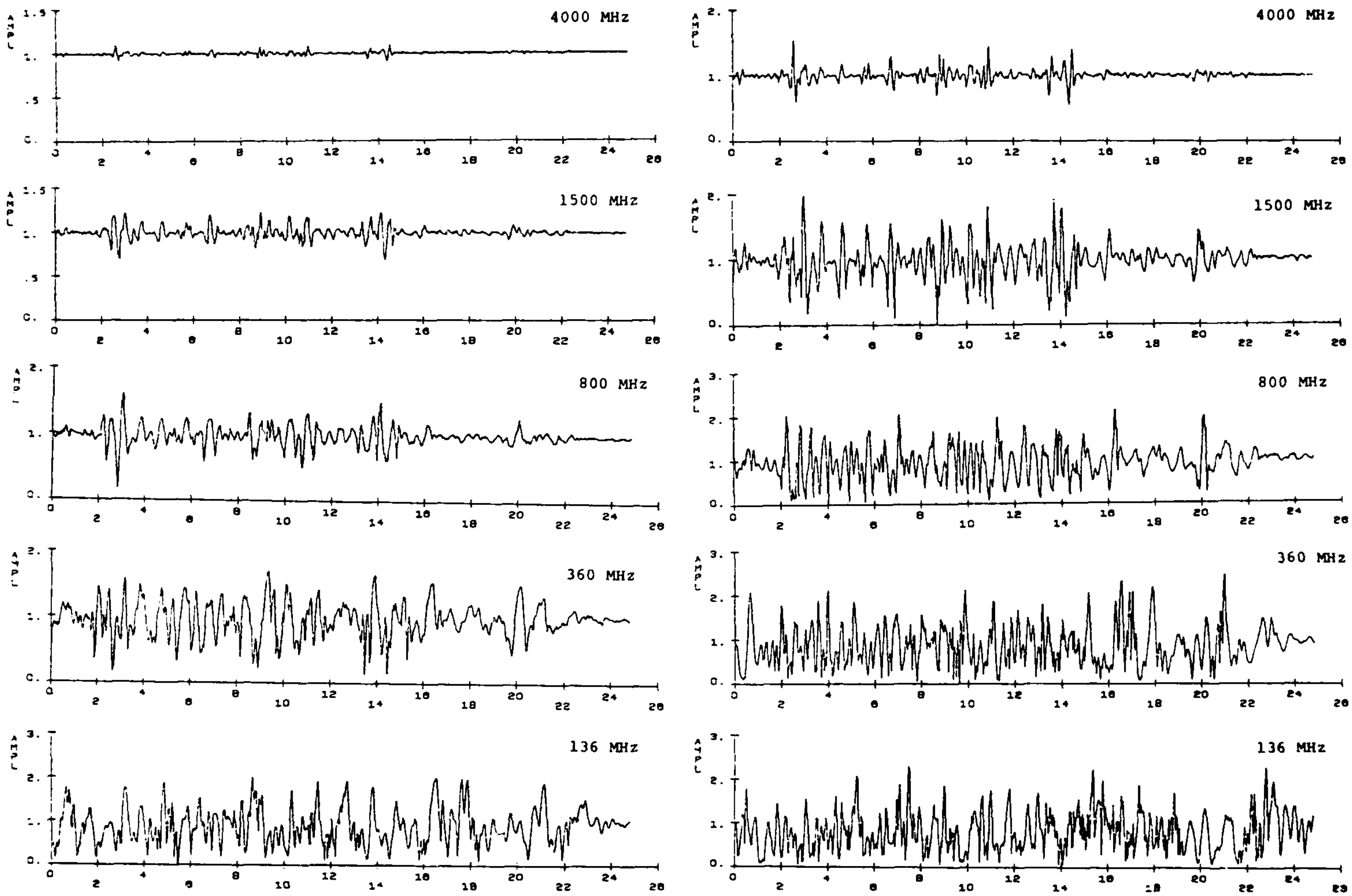



FIGURE 4

A. Amplitude pattern at different frequencies produced by the initial stage bubble.

B. The same as in Figure 8 but for the developed stage bubble.

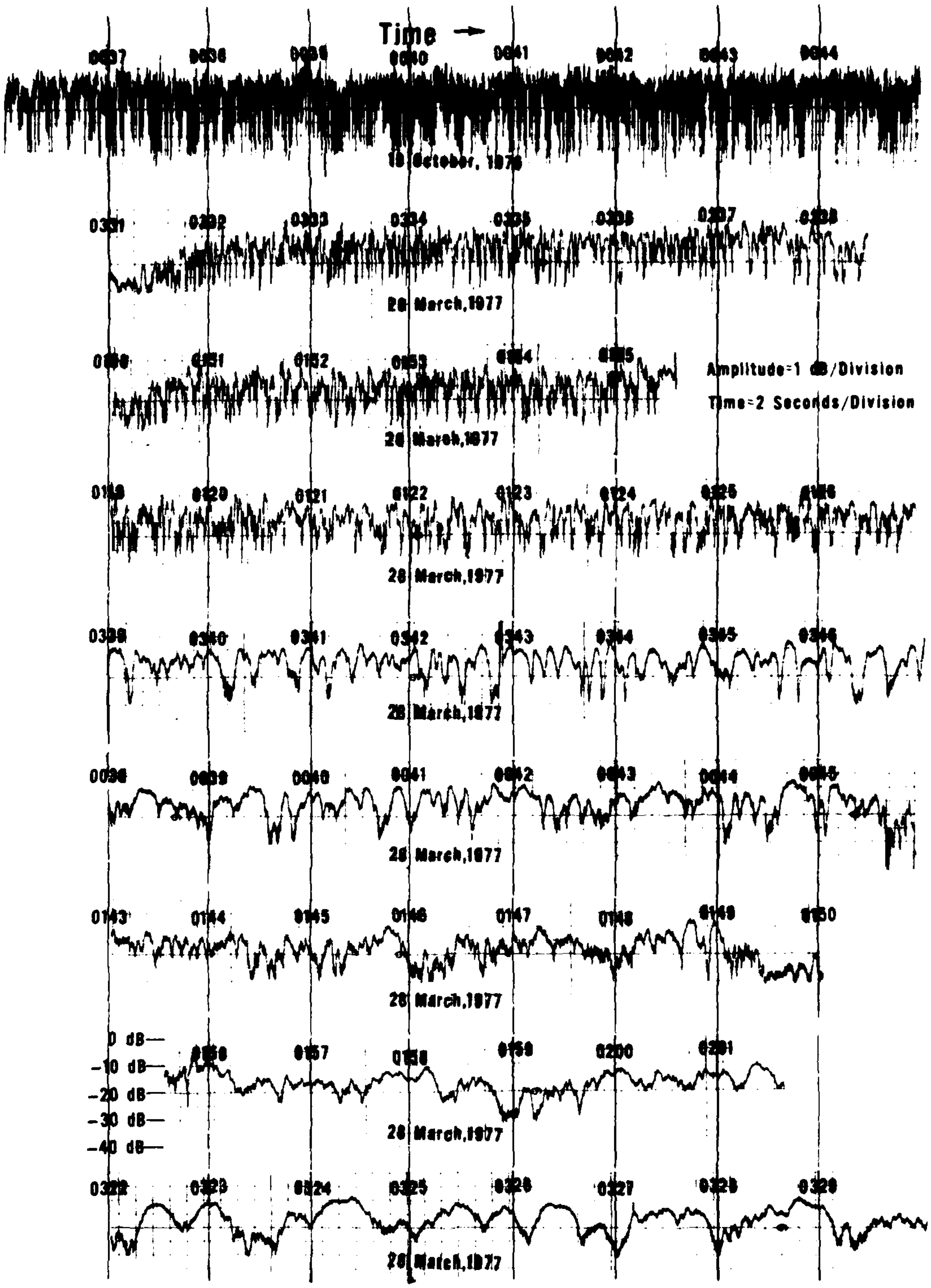



Figure 5. Equatorial UHF Ionospheric Scintillation Fade Variations ( From Johnson[13,24] )

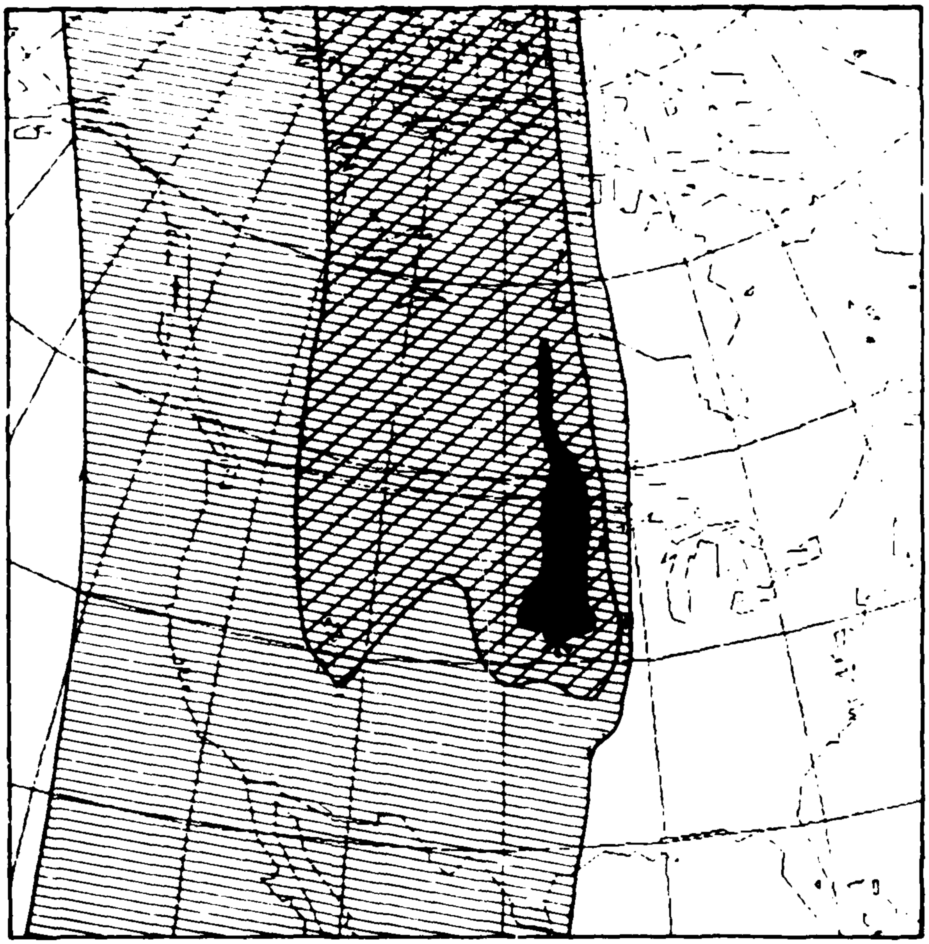


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FIGURE 6. (U) EXAMPLE OF CALCULATED EXTENT OF INTENSE UHF SCINTILLATION AND ABSORPTION AT ONE-HALF HOUR. Hatched region shows extent of intense scintillation (see Figure 7). UHF scintillation may be more extensive if ambient F region is striated. Scintillation is likely to be very fast within double-hatched region. Black region shows extent of 10-dB or greater absorption at UHF.

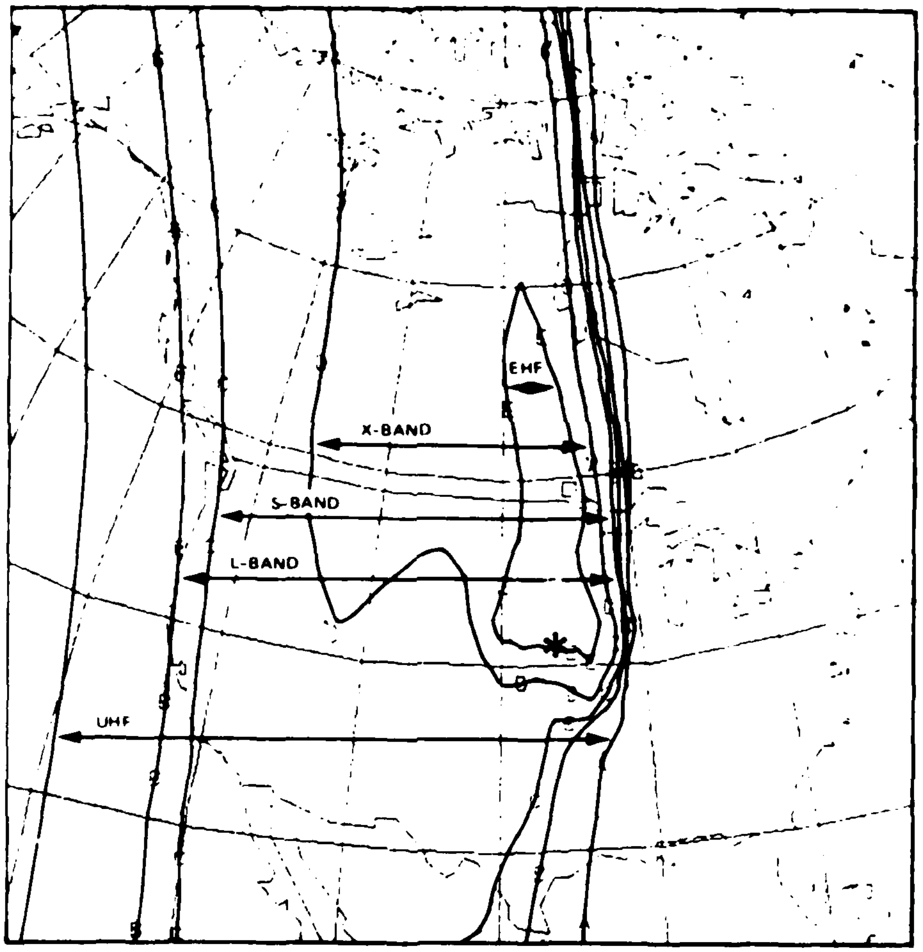


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FIGURE 7. (U) COMPARISON OF CALCULATED EXTENT OF INTENSE SCINTILLATION AS A FUNCTION OF FREQUENCY AT ONE-HALF HOUR. Extent of EHF scintillation is particularly sensitive to uncertainties and may be smaller than shown.

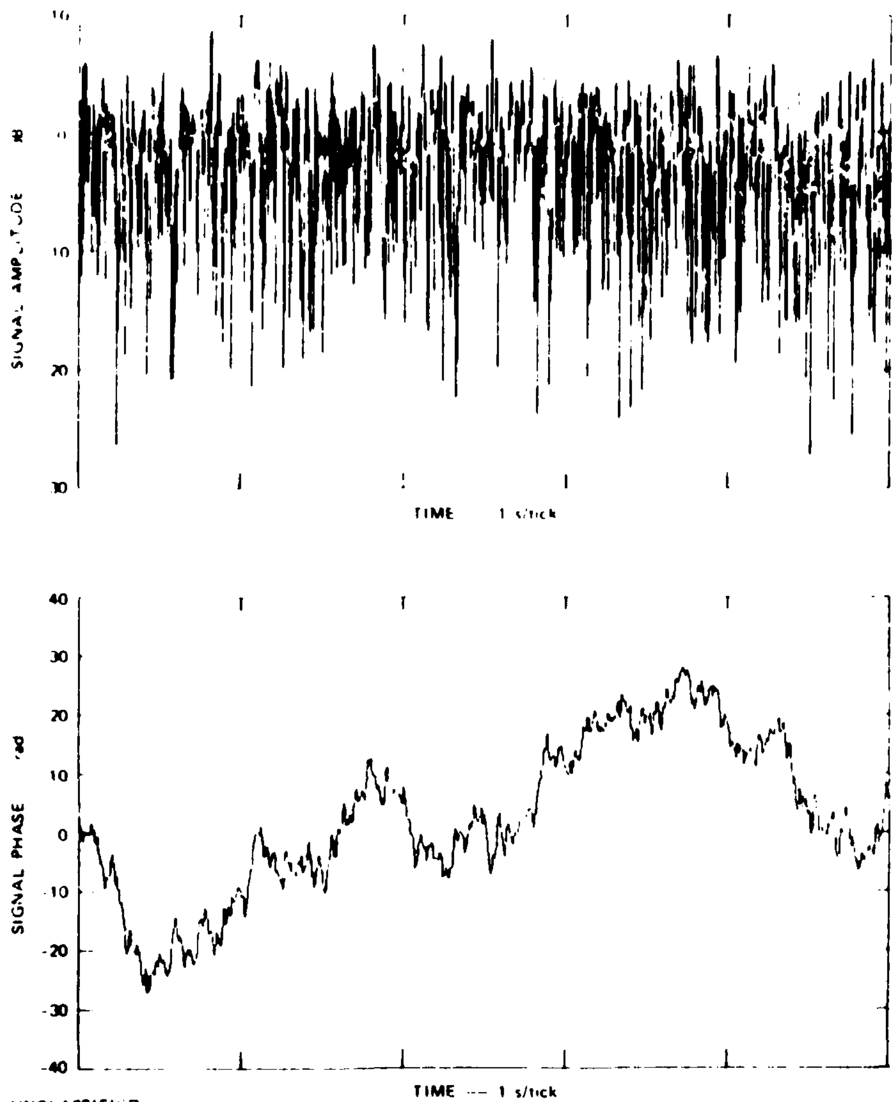


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FIGURE 3. (U) EXAMPLE OF UHF SIGNAL AMPLITUDE AND PHASE SCINTILLATION ($\tau_0$ = 8 ms). Scintillations can be faster or much slower, depending on link geometry and terminal motion.

# APPENDIX A

## PROPAGATION DISTURBANCES DUE TO INCREASED IONIZATION*

| Disturbance | Frequency Dependence | UHF (300 MHz) | L-Band (1.5 GHz) | S-Band (2.25 GHz) | X-Band (7.5 GHz) | EHF (30 GHz) |
|---|---|---|---|---|---|---|
| Disturbances due to mean ionization | | | | | | |
| Absorption (dB) | $f^{-2}$ | 15 | 0.6 | 0.3 | 0.02 | 0.001 |
| Phase shift (rad) | $f^{-1}$ | 28000 | 56000 | 37000 | 1120 | 280 |
| Group delay (s) | $f^{-2}$ | $1.5 \times 10^{-5}$ | $6.0 \times 10^{-7}$ | $2.7 \times 10^{-7}$ | $2.4 \times 10^{-8}$ | $1.5 \times 10^{-9}$ |
| Group delay dispersion (ns/MHz) | $f^{-3}$ | 100 | 0.8 | 0.2 | $6 \times 10^{-3}$ | $1 \times 10^{-4}$ |
| Disturbances due to striated ionization | | | | | | |
| Amplitude scintillation | Complicated | Saturated (Rayleigh) | Saturated (Rayleigh) | Saturated (Rayleigh) | Saturated (Rayleigh) | Moderate to saturated |
| Phase standard deviation (rad) | $f^{-1}$ | 3500 | 700 | 470 | 140 | 35 |
| Signal decorrelation time | Complicated | See discussions Reference 19 | | | | |
| Correlation bandwidth | Complicated | See discussions Reference 19 | | | | |
| Angular scatter (rad) | $f^{-2}$ | 0.5 | $2 \times 10^{-2}$ | $9 \times 10^{-3}$ | $8 \times 10^{-4}$ | $5 \times 10^{-5}$ |
| Group delay Fluctuations due to fluctuations in total electron content (s) | $f^{-2}$ | $1.8 \times 10^{-6}$ | $7 \times 10^{-8}$ | $3 \times 10^{-8}$ | $3 \times 10^{-9}$ | $1.8 \times 10^{-10}$ |
| Time delay jitter and spread due to angular scatter | $f^{-4}$ | (Values depend on propagation geometry) | | | | |

*Specific example for idealized 100-km-thick slab of $10^8$ el/$cm^3$ structured ionization. Values are illustrative only, and do not represent a worst-case environment. Disturbances can be more or less severe depending on scenario, link geometry, and time after burst.

## APPENDIX B

### SUMMARY OF SATELLITE LINK EFFECTS AND MITIGATION METHODS

| Frequency | Satellite Systems | Extent and Duration of Major Effects | Dominant Degradation Effects | Mitigation Methods |
|---|---|---|---|---|
| UHF (225-400 MHz) | Strategic Missions AFSATCOM FLTSATCOM | Absorption over hundreds of kilometers lasting tens of minutes | Loss of $E_b/N_o$ below demodulation threshold | Increased EIRP (not very effective); multiple redundant links |
| | | Scintillation over thousands of kilometers for hours in striated regions for high-altitude bursts | Severe phase and amplitude fading with slow to very fast fade rates | Optimal demodulator design, coding, interleaving, repetition, increased EIRP |
| | | Scintillation over CONUS-sized regions for hours in striated ambient F region from bursts at any altitude | Moderate to severe phase and amplitude fading with slow to moderate fade rates, comparable to severe natural scintillation | Optimal demodulator design, coding, interleaving, repetition, increased EIRP |
| L, S Bands (1.2-2.3 GHz) | GPS Navigation DSP Data Links | Absorption over tens of kilometers lasting few minutes | Loss of $E_b/N_o$ | Increased EIRP Link redundancy |
| | | Scintillation over thousands of kilometers for hours in striated regions from high-altitude bursts | Severe phase and amplitude fading with slow to very fast fade rates | Optimal demodulator design, coding, interleaving (GPS) increased EIRP, multiple links, spaced antennas (DSF) |
| | | Scintillation over CONUS-sized regions for hours in striated ambient F region from bursts at any altitude | Moderate to severe phase and amplitude fading with slow to moderate fade rates, comparable to severe natural scintillations | Optimal demodulator design, coding, interleaving (GPS) increased EIRP, multiple links, spaced antennas (DSP) |

APPENDIX B (Cont)

| Frequency | Satellite Systems | Extent and Duration of Major Effects | Dominant Degradation Effects | Mitigation Methods |
|---|---|---|---|---|
| X-Band (7.2-8.4 (GHz) | DSCS Other proposed links | Absorption over tens of kilometers for few seconds | Transient loss of $E_b/N_o$ | Increased EIRP, link redundancy |
| | | Scintillation over hundreds to thousands of kilometers for hours in striated regions from high-altitude bursts | Moderate to severe phase and amplitude fading with slow to fast fade rates | Optimal demodulator design, coding, interleaving, repetition (some links), increased EIRP, multiple links |
| | | Dust and/or water vapor (or ice) from surface or near-surface bursts over tens of kilometers for hundreds of seconds | Potential deep amplitude and phase scintillations with moderately fast fade rates | Optimal demodulator design, coding, interleaving, repetition (some links), increased EIRP, multiple links |
| EHF (30-45 GHz) | AFSATCOM (SSS/NFCS) Other proposed systems | Scintillation over hundreds of kilometers for about an hour in striated regions from high-altitude bursts | Moderate to severe phase and amplitude fading with moderate fade rates along some paths | Optimal demodulator design, coding, interleaving, repetition (some links), increased EIRP multiple links |
| | | Dust and/or water vapor (or ice) from surface or near-surface bursts over tens of kilometers for tens of minutes | Moderate attenuation and severe phase and amplitude scintillation | Optimal demodulator design, coding, interleaving, repetition (some links), increased EIRP, multiple links |
| | | Tropospheric effects (clouds, rain, etc.) | Attenuation of $E_b/N_o$, scintillations | Optimal demodulator design, coding, interleaving, repetition (some links), increased EIRP, multiple links |

* Possible degradation due to dispersion, noise, and other effects may be a problem, depending on specific system characteristics.

# APPENDIX C

## HIGH LATITUDE SCINTILLATION LEVELS TAKEN AT 137 MHz (from the ATS-3 Satellite)

Aarons[2] made measurements of the 137 MHz beacon on ATS-3 at 3 sites along 70° west meridian to obtain data to derive empirical analytical formulations for the average scintillation at sub-auroral and auroral latitudes. The data base was 15 minute scintillation indices of 3-7 years taken at Sagamore Hill, Mass, Goose Bay, Labrador, and Narssarssuaq, Greenland. The coordinates of the observational sites are as follows:

Table 1. Coordinates of Observational Sites

| Station | Geographic Corrdinates Latitude | Geographic Corrdinates Longitude | Invariant Latitude | Elevation Angle | Azimuth | Zenith Angle | Ionospheric Propagation Angle |
|---|---|---|---|---|---|---|---|
| Narssarssuaq | 54.2° | 51.0° | 63.2° | 18.0° | 208° | 64° | 124° |
| Goose Bay | 48.3° | 61.7° | 60.3° | 28.8° | 191° | 56° | 136° |
| Sagamore Hill | 39.3° | 70.6° | 53.5° | 40.9° | 178° | 46° | 154° |

Aarons derived distributions of the occurrences at various levels of scintillation which permits evaluation of the degradation potential of auroral scintillation on present or proposed systems. The data is partitioned into two significant scintillation blocks: 6dB and 9dB. Data is further divided into night (17-05LT) and day (05-17LT). Planetary magnetic indices ($K_p$) taken during the observational period were assigned into two groups $K_p$=0-3+ and $K_p$=4-9.

Table II summarizes the Percentage of Occurrence Data.

APPENDIX C

TABLE 2

PERCENTAGE OF OCCURRENCE

OF SCINTILLATIONS

AT THREE AURORAL SITES

Data at 137 MHz from ATS-3

| Site | Magnetic Index ($K_p$) Range | Scintillation Block (dB) 6 dB 9 dB | Percentage of Occurrence Night (17-05LT) | Day (05-17LT) |
|---|---|---|---|---|
| Narssarssuaq | $K_p$ = 0-3 | 6dB | 46.3% | 14.5% |
| | | 9dB | 29.4% | 6.2% |
| | $K_p$ = 4-9 | 6dB | 78.8% | 47.2% |
| | | 9dB | 61.8% | 31.0% |
| Goose Bay | $K_p$ = 0-3 | 6dB | 8.3% | 0.5% |
| | | 9dB | 3.9% | 0.2% |
| | $K_p$ = 4-9 | 6dB | 30.2% | 8.3% |
| | | 9dB | 15% | 3.7% |
| Sagamore Hill | $K_p$ = 0-3 | 6dB | 5.4% | 0.3% |
| | | 9dB | 2.5% | 0.1% |
| | $K_p$ = 4-9 | 6dB | 6.9% | 0.7% |
| | | 9dB | 3.6% | 0.3% |

## APPENDIX D

## SCINTILLATION CLASSIFICATION

### A. Scintillation Indices.

The depths of scintillation fading are measured by the indices $S_1$, $S_2$, $S_3$, and $S_4$ defined by Briggs[8]. These indices are essentially the mean deviation ($S_1$, $S_3$,) or the root-mean-square deviation ($S_2$, $S_4$,) of the received amplitude ($S_1$, & $S_2$) or power ($S_3$, $S_4$). $S_4$, called the scintillation index, has been widely used because it is amenable to theoretical interpretation.[3] The Joint Satellite Studies Group (JSSG) has adopted an alternative method, somewhat less rigorous, to insure standard methods of scaling and statistical analysis called Scintillation Index $_{JSSG}$ = $S.I_{JSSG} = \dfrac{P_{MAX} - P_{MIN}}{P_{MAX} + P_{MIN}}$

$P_{MAX}$ = Power amplitude of 3rd peak down from the maximum excursion of scintillations.

$P_{MIN}$ = Power amplitudes of the third peak up from the minimum excursions measured in dB (Whitney, 1969).

Comparison of selected values of these indices follow:

| $S_4$ | dB | $SI_{JSSG}$ |
|---|---|---|
| 0.75 | 1 | 11 |
| 0.17 | 3 | 32 |
| 0.30 | 6 | 59 |
| 0.45 | 10 | 81 |

### B. Fading Probability Distribution.

The scintillation indices alone do not fully describe the fading characteristics of the signal unless supplemented by amplitude probability distribution and fading rates. In the case of severe scintillations (of 20dB or more below average received signal energy) the received signal distribution is Rayleigh distributed; departures from this distribution occur mainly at weaker fading intensity. In weak scintillation the power spectral density (PSD) of signal intensity fluctuations typically exhibits a $f^{-3}$ rolloff characteristic, where f is the fluctuation frequency; in strong scintillations, rolloff usually occurs at a weaker rate of about $f^{-1.2}$. Correlation time decreases as scintillation intensity increases, and correllation times, computed or observed for weak scintillation, are maximum value for fixed transmission geometrics, i.e., fade duration varies, for fixed transmission geometrics[7].

## C. Scintillation Fading Rates

An additional signal parameter affecting link performance in scintillation conditions is the scintillation fading rate. This is measured by the signal decorrelation time $t_o$ (tau$_o$). Values of $t_o$ range from about 1 millisecond to 10 seconds.

Satellite systems must be designed to operate over a very wide range of scintillation rates if the links are to survive in the presence of scintillation disturbances.

Additional comments on the implications of scintillation rates appear in the mitigation section.

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## List of Abbreviations, Acronyms & Symbols

| | |
|---|---|
| AFSATCOM | Air Force Satellite Communication |
| AJ | Anti-jam |
| AS | Anti scintillation |
| C/No | Carrier Power-to-Noise density ratio |
| CONUS | Continental United States |
| DSCS | Defense Satellite Communication System |
| DNA | Defense Nuclear Agency |
| DSP | Defense Support Program |
| EAM | Emergency Action Message |
| $E_b$/No | Information-bit-energy-to-noise-density ratio |
| EHF | Extremely High Frequency (30-300 Gigahertz) |
| EIRP | Effective Isotropic Radiated Power |
| GPS | Global Positioning Satellite |
| HANE | High Altitude Nuclear Explosion |
| PN | Pseudonoise |
| PSD | Power Spectral Density |
| SIOP | Single Integrated Operating Plan |
| SACCA | Strategic Air Command Communications Area |
| SSS | Strategic Satellite System |
| SHF | Super High Frequency (3-30 Gigahertz) |
| TAU | ($t_0$) Auto correlation time for intensity of fade rate (reciprocal) |
| TEL | Total Electron Content |
| UHF | Ultra High Frequency (300-3000 Megahertz) |
| VHF | Very High Frequency (30-300 Megahertz) |
| TIME (early) | First 20 minutes following nuclear detonation |
| TIME (late) | Time after 20 minutes following nuclear detonation |

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